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A practical approach for increasing penetration in hybrid laser-arc welding of steel

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Abstract

Hybrid laser-arc welding of thick-section steel requires high power lasers, appropriate process parameters, and alternative techniques for obtaining deeper penetration. Conventional techniques for increasing penetration/efficiency include groove beveling, preheating, and the use of pre-set gap, but they are costly and inconvenient. Therefore, investigating alternative approaches for increasing process efficiency is of great importance. Recent studies on laser welding of steel reveal that the edge surface roughness, geometry, and preparation method of the joint can influence the penetration in a butt joint configuration. In this study, a number of experiments were carried out on 25 mm steel plates using current industrial procedures. Common industrial preparation methods such as standard quality machining and pre-set gap were compared with alternative methods providing different edge surface roughness values and roughness patterns. The results showed that the preparation of edge surface quality should be considered as an alternative approach for increasing process efficiency.

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Keywords: Hybrid laser welding; edge surface morphology; weld penetration.

1. Introduction

The development of high power solid-state lasers has led to increased interest in hybrid laser-arc welding (HLAW). When it comes to applications involving the manufacture of heavy sections, the unique advantages of new solid-state laser systems make them far more attractive than the previous generation of high power CO_2 lasers (Gumenyuk and Rethmeier (2013)). Examples of these applications include the use of HLAW in shipbuilding, wind turbine structures, offshore constructions, and the fabrication of large diameter oil and gas pipelines.

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The HLAW of thick-section steels requires high brightness, high power lasers, appropriate process parameters, and alternative techniques for obtaining deeper penetration. However, as the power level of current commercial lasers is technologically limited, welding greater thicknesses can be challenging. A great deal of experimental research has been conducted on the HLAW of thick section steel. Vollersten et al. (2010) and Rethmeier et al. (2009) suggest using either a beveled groove or preheating to increase penetration. Another conventional technique for increasing penetration is the use of a pre-set gap. Depending on the plate thickness, Webster et al. (2008) suggested a certain gap to increase penetration, thus boosting process efficiency. However, these techniques have drawbacks of their own. Beveling is the most commonly used technique, but it is costly. Preheating is not only costly but also inconvenient, especially for the manufacture of large structures. Moreover, the processing of thick materials involves the positioning of large workpieces, making it difficult (if not impossible) to keep a constant gap throughout the joint (Seffer et al. (2014)). Consequently, a varying gap, including zero gap, must be considered for the welding (Webster et al. (2008)).

These issues mean that the investigation of alternative solutions for increasing process efficiency is of great importance. For instance, the geometrical and physical characteristics of the weld groove surface must be considered in order to improve the energy coupling into the workpiece. On the basis of the results of absorptance measurements in Bergstrom et al. (2007) that were preformed for solid-state lasers at wavelengths of 1.053 and 0.527 μm, it is evident that surface roughness, surface oxides, surface contamination, and the presence of alloying elements in the steels can increase absorptance. Moreover, according to Kaplan (2012), an analytical investigation of the absorptivity of 1 μm laser rays across a wavy molten steel surface has shown that even a rather low level of roughness (of the order of 5-7 μm) strongly modulates the local absorptivity across the surface. Recent experimental studies on the solid-state laser welding of steel reveal that the edge surface roughness, geometry and preparation method of the joint have a significant influence on penetration in a butt joint configuration. In Farrokhi et al. (2015), a study of the HLAW of 25 mm steel with different edge surface roughness showed that the welding of samples with sand-blasted laser cut surfaces required less laser energy than the welding of samples that had been prepared by water jet cutting or milling. In Sokolov et al. (2015), a study of reduced pressure laser welding of 40 mm thick steel revealed that the combination of increased edge surface roughness and a pre-set gap increases the weld penetration. Moreover, an earlier study investigated the influence of edge surface roughness on laser absorption at power levels of above 10 kW (Sokolov et al. (2012)). From the latter, it is evident that the influence of cut quality and surface roughness must be taken into consideration when laser welding heavy section steel, as the processing of higher thicknesses requires laser power levels higher than 10 kW.

So far, only standard milling has been used for groove preparation prior welding in the vast majority of HLAW research. Very few studies have been published on the effect of edge surface quality on laser absorption and on the efficiency of the subsequent welding process. Despite the importance of adequate topography in surface quality evaluation, the effect of different roughness patterns has not been taken into account. Moreover, in Bergstrom et al. (2007), the absorptance measurements were performed at room temperature within a range of 0.05 to 5.6 μm average roughness, and there is not enough knowledge about the absorption characteristics in weld grooves at elevated temperatures with roughness values extending far above this limited range. In Sokolov et al. (2012), the research was limited to a range of 1.6 to 8 μm average roughness because at levels higher than 8 μm, the quality of autogenous laser welding was unacceptable. With hybrid laser welding, however, this range is more flexible due to the better bridgeability of the process.

To address these issues, this study aims to investigate the effect of different edge surface qualities, including both roughness value and its pattern, on the subsequent HLAW of steel. For this reason, different edge surface roughness levels have been chosen for the study, ranging from the common industrial milling quality to roughness levels above 8 μm. In addition, the influence of differences in pre-set gap has been taken into account to allow comparison with the influence of edge surface preparation as an alternative approach for increasing process efficiency.

2. Experimental Procedure

2.1. Materials and preparation procedure

To investigate the effect of different edge surface qualities on subsequent welding process efficiency, the samples were prepared with four different qualities to study the influence of surface roughness and roughness patterns (see Figure 1).

Qualities 1, 2, and 3 were prepared by means of the common industrial milling method for investigating the effect of surface roughness. The samples were prepared with the same milling machine, but with different tools and parameters to provide three roughness levels. Edge surface quality 4 was considered to have nearly the same average roughness value as quality 3, except that it had a different roughness pattern. For this reason, surface quality 4 was obtained by laser cutting, using the process parameters in Table 1. This allowed investigation of the effect of different surface patterns. It should be noted that even during laser cutting with nitrogen gas the cut surface might become oxidized. This is due to the fact that during the cutting, the cut surface area that is outside of the nitrogen coverage area might be exposed to oxygen at the elevated temperatures. For this reason, in this experiment, the laser cut samples were sand-blasted to remove the oxide layer from the cut surface. In addition, all the samples with milled edges were cleaned by alcohol to remove the water-miscible coolant liquid from the surfaces.

Figures 2 to 5 show the results of surface topography. The milled surfaces have a clear pattern created by the rotation of the milling tool. However, surface quality 4 exhibits a different pattern of striations created by laser cutting, even though it has nearly the same root mean square (S_q) value as surface quality 3. The profilometry and surface roughness measurements were performed within a 24 mm x 24 mm area using an Alicona Infinite Focus optical profiler. Post-processing and the analysis of the surface measurements as well as void volume computation used SPIP software. Linear plane correction and Gaussian long wave filtration were applied to the measurements. The extreme noise values were eliminated from the evaluation so that the eliminated area did not exceed the 0.5% of the total area. In addition to S_q, the average roughness (S_a), peak to peak roughness (S_z), maximum valley depth (S_v), and maximum peak height (S_p) were considered for 3D roughness measurement. Moreover, the average surface roughness (R_a) and root mean square (R_q) were measured in 2D on three different sections of the surfaces (see Figures 2 to 5).

Table 1. Laser cutting process parameters.

Travel speed (mm/min)	Gas type	Gas pressure (bar)	Nozzle standoff (mm)	Nozzle diameter (mm)	Laser power (kW)	Focal length (mm)	Focal point position (mm) *
50	N_2	7.5	0.85 ± 0.1	2.5	3	470	-12.5

* below the workpiece surface.

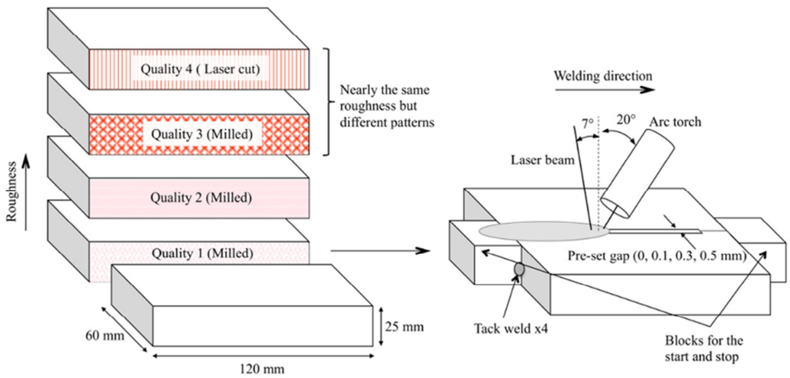
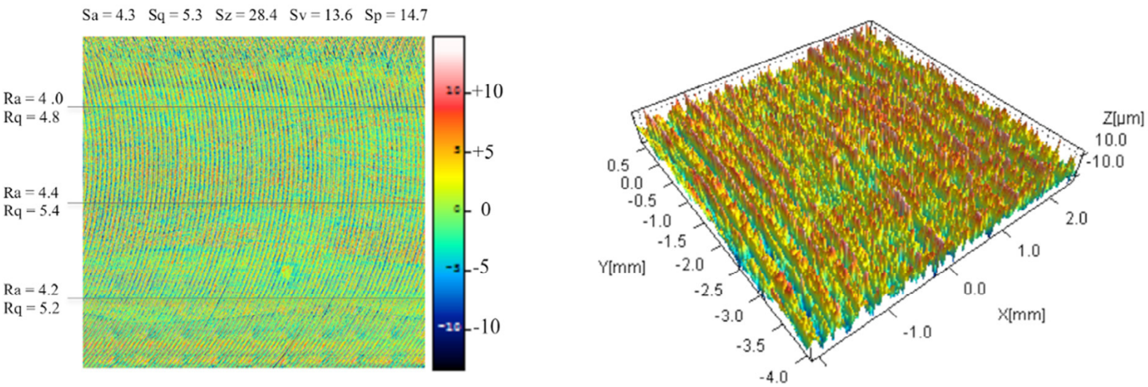
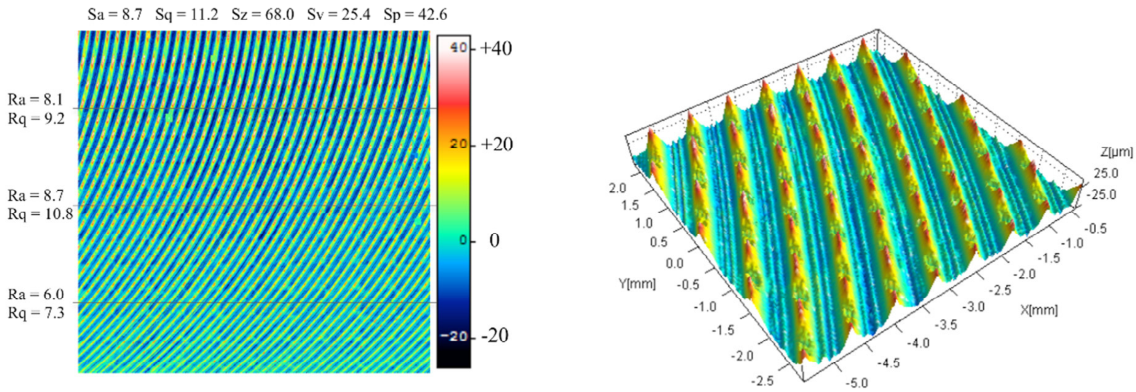


Fig. 1. The schematic preview of the experimental procedure. The vertical dashed line is perpendicular to the plate.



(a) (b)

Fig. 2. Quality 1 (industrial milling): (a) surface roughness results (in µm). (b) 3D profilometry of a 5 mm x 5 mm area.



(a) (b)

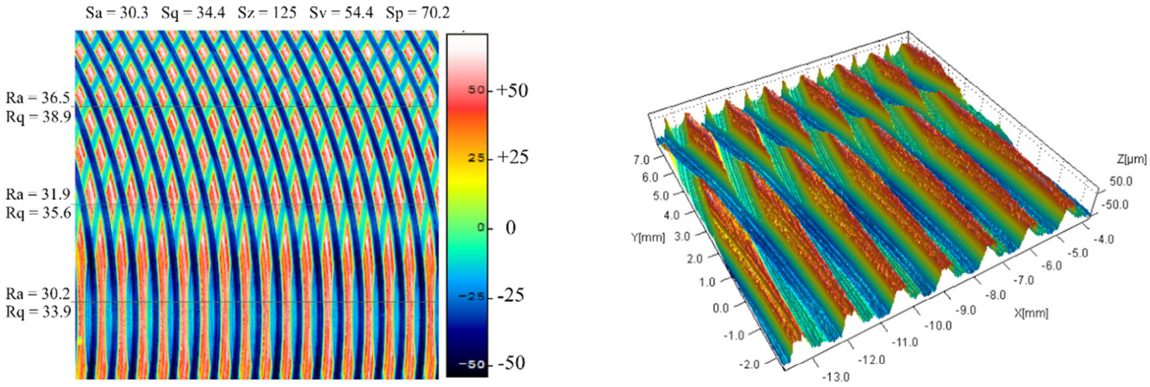
Fig. 3. Quality 2 (rough milling): (a) surface roughness results (in µm). (b) 3D profilometry of a 5 mm x 5 mm area.

The laser used for cutting was an IPG Photonics YLS- 3000SM fiber laser providing a 3 kW single-mode continuous-wave laser beam with a wavelength of 1076 nm. The laser was guided through an optical fiber to a HighYag cutting head. The setup for cutting is shown in Kristiansen et al. (2013). S355J2 steel plates with the dimensions shown in Figure 1 were used for the experiments. The chemical composition of the steel can be found in table 2. Since the gap tends to vary during welding, the plates had to be pressed together firmly. To achieve this, two blocks of the same material as the plates were tack welded to both sides of the samples. This also made it possible to keep the start and stop points of the welding process outside the main plate. Figure 1 shows an overview of the experimental setup.

It should be noted that all the above mentioned samples were prepared for zero pre-set gap experiments. However, to allow comparison, some experiments having surface quality 1 were also carried out with 0.1, 0.3, and 0.5 mm pre-set gaps. For this reason, some samples were machined precisely at the edge so that the desired pre-set gap was guaranteed constantly all along the edge of the sample (see Figure 1).

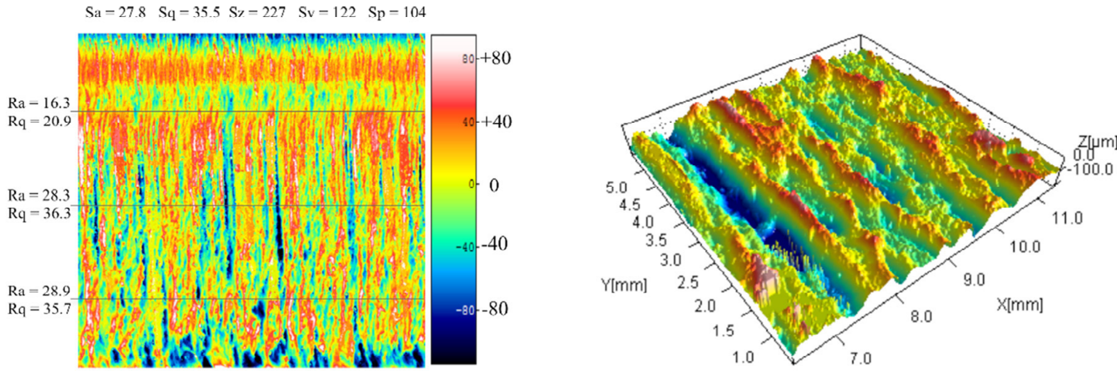
Table 2. Chemical composition of the steel (%) (after the material certificate provided by the steel manufacture).

	C	Mn	P	S	Si	Cu	Al	Ni	Cr	V	Mo	CEV
S355J2	0.16	1.43	0.009	0.003	0.20	0.02	0.036	0.02	0.02	0.001	0.003	0.40



(a) (b)

Fig. 4. Quality 3 (rough milling): (a) surface roughness results (in µm). (b) 3D profilometry of a random 10 mm x 10 mm area.



(a) (b)

Fig. 5. Quality 4 (sand-blasted laser cut): (a) surface roughness results (in µm). (b) 3D profilometry of a random 5 mm x 5 mm area.

2.2. Welding Procedure

Double-sided single-pass HLAW was performed to achieve sufficient penetration, meaning that first, one side was welded and then the sample was turned around to weld the second pass on the other side. The travel speed was adopted as the critical parameter for evaluating the process efficiency. Some other parameters such as wire feed and arc power were varied to compensate for the lack of heat and filler material with the increase of travel speed. The other process parameters were kept constant to simplify the study. Tables 3 and 4 show the constant and variable parameters, respectively for each pass. It should be noted that to allow comparison, when welding with a given travel speed, the same corresponding parameter set was used regardless of the samples surface quality or pre-set gap. The laser used for HLAW was a Trumpf TruDisk 16002 disk laser providing a 16 kW, continuous wave laser beam with a wavelength of 1030 nm. The laser was guided through an optical fiber to a Trumpf RFO Reflecting Focus Optics. The HLAW was provided using the combination of the laser and a MAG system with a gas containing 92Ar $8CO_2$. The filler material was ESAB OK 12.50 filler wire with a diameter of 1.2 mm. The welding was performed using an arc-leading process (see Fig. 1), in which the arc was exposed 1 second before the laser hit the weld pool. After the welding, radiographic examination was performed to detect possible porosity and cracks in the welds. For this reason, the weld samples were exposed to 210 kV x-ray radiation so that the IQI (wire) sensitivity was 1.6%. Macro-section samples were cut out from each weld for the evaluation of penetration. Only a length of 70 mm in the middle of the weld was used in the quality evaluation.

Table 3. Welding process parameters (for the variables see table 4.).

Laser power (kW)	Arc power (kW)	Wire feed (m/min)	Travel speed (m/min)	Gas flow rate (l/min)	Focal position (mm)	Focal length (mm)	Laser angle (degree)	Arc torch angle (degree)	Wire stickout (mm)	Arc-laser distance (mm)
14	3-21	5-22	2.3-6.2	25	-10**	600	-7*	20*	25	3

* With respect to the vertical axis. ** Below the workpiece surface.

Table 4. Welding process variable parameters for the corresponding travel speeds (for each pass).

	Travel speed (m/min)										
	2.3	2.6	2.9	3.2	3.5	3.8	4.1	4.7	5.6	5.9	6.2
Wire feed (m/min)	5	5	7	8.5	9.5 (18*)	10.5 (20*)	11.5 (22*)	13.5	16.5	17.5	18.5
voltage (V)	21	21	27	34	38 (44*)	41 (45*)	43 (47*)	43	44	44	44
current (A)	150	150	232	267	312 (450*)	338 (475*)	365 (500*)	391	430	443	456

* Corresponding parameters for the experiment with 0.5 mm gap.

3. Results and discussion

The summary of the welding results can be found in Figure 6, which shows all the experimental points based on the different surface qualities, the pre-set gaps and the corresponding travel speeds. The figure compares the effect of surface preparation versus gap increase on the maximum travel speed for full penetration. Surface quality 1 and 2 with zero pre-set gap led to the lowest maximum travel speed for full penetration, which was 2.3 m/min. As the pre-set gap increased and the surface quality remained the same, the maximum travel speed for full penetration increased up to 3.8 m/min. The improvement in penetration produced by increasing the pre-set gap was expected as it was already anticipated in industry. Depending on the welding process and as long as it remains within a certain range that can be bridged, a wider gap normally allows more filler material inside the weld, thereby increasing the penetration or travel speed. In this experiment, on the other hand, the surface quality varied while the pre-set gap remained constant (zero), and the maximum travel speed for full penetration could be influenced significantly. As can be seen in the figure, a steady increase in travel speed was obtained by using samples having sand-blasted laser cut surface (surface quality 4), which guaranteed the maximum travel speed of 5.3 m/min. However, an increase of average surface roughness to 9 µm could not enhance the process efficiency, as the maximum speed was 2.3 m/min when the samples had surface quality 2. When average surface roughness rose to 30 µm, travel speed increased slightly to 2.9 m/min, but this was still far lower than the result achieved for surface quality 4.

Figure 6 shows that surface preparation can be considered an alternative approach for increasing travel speed or penetration in the HLAW of steel. Moreover, welding process was more stable with quality 4 surfaces than with other quality surfaces. Neither x-ray tests nor macro-section inspection detected any pores in the welds that were made using surface quality 4. In some cases the other experiments tended to produce pores in the weld. Solidification cracks were unavoidable in the experiments, regardless of their edge surface quality. This is because the travel speed range used in this study was too high, leading to high cooling rates and low width-to-depth ratios. Figure 7 shows an example of full penetration and not full penetration experiments. As can be seen, very small vertical flaws appeared in the laser-dominated area of welds. The flaws were not continuous and their size was some times too small. Therefore, in some cases it was not possible to even detect them by radiographic examination.

Comparison of the maximum travel speeds obtained by the experiments with surface quality 3 and 4 leads to the conclusion that the average surface roughness was not solely responsible for the increase in travel speed. In fact, other characteristics of surface quality 4 could explain the increase:

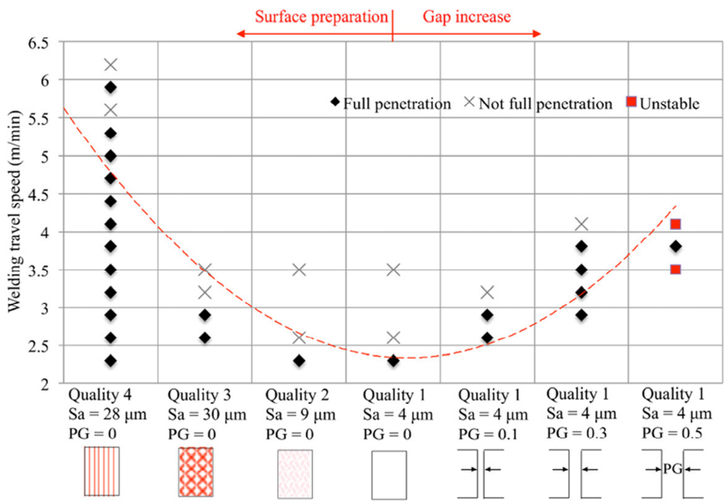


Fig. 6. Comparison of surface preparation and gap increase approaches in terms of welding travel speed and penetration. PG: pre-set gap. Red dashed line: polynomial fit to the maximum travel speeds for full penetration, showing the distribution direction of the experimental points.

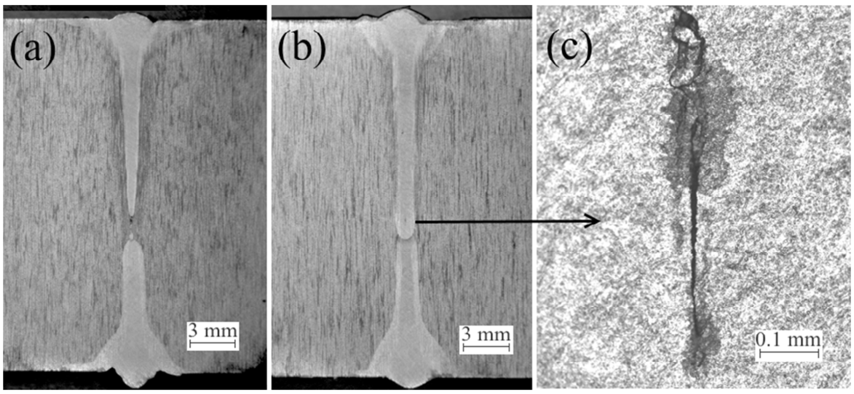


Fig. 7. (a) An example of incomplete penetration experiment (6.2 m/min, surface quality 4, zero pre-set gap), (b) a full penetration experiment with a flaw in the middle (3.8 m/min, surface quality 4, zero pre-set gap), and (c) microscopic image of the flaw.

- (1) the "natural gap" due to peaks and valleys of surface roughness;
- (2) the different chemical composition of the sand-blasted laser cut surface due to the presence of silica;
- (3) the chaotic striations pattern of the laser cut surface, which could increase laser absorption or enhance the molten filler material flow inside the joint;
- (4) the different surface microstructure due to the heat treatment during laser cutting.

Items (1), (2), and (3) will be discussed briefly in the following section as the main explanations for this phenomenon. However, the limitations of this study did not allow scope for the investigation of item (4), so it was considered for future studies.

3.1. Natural gap effect

In general, the peaks and valleys of edge surface roughness lead to the formation of local gaps in the joint, and the local gaps on the rough surfaces provide a "natural gap" in the joint that is unavoidable even if the pre-set gap is set to zero. Consequently, in this study, the increased penetration/speed in the experiments with higher surface roughness might also have been due to local gaps allowing more heat and filler material further inside the weld. This implies that it is very important to take the presence of natural gap into account when using samples with rough edge surfaces. In the case of the milled surfaces investigated, the maximum possible natural gap could be estimated by measuring the R_z value (Figure 8 a), as the roughness distribution was more systematic than the chaotic striations of laser cut surfaces (Figure 8 b). However, an estimation based on the 2D roughness profile could not provide an accurate indication of the natural gap, as the peaks and valleys of the two confronting surfaces are randomly paired in a real joint. Consequently, the void volume above the 3D surface profile was considered for the evaluation as it could provide a better estimation of volumetric natural gap throughout the surfaces of the samples. Figure 8c depicts the definition of the void volume for the evaluation. The void volume on the 3D surface roughness profiles was computed over the complete surface measurement area of 24 mm x 24 mm. Assuming that both pieces of a butt joint have identical edge surface quality, the void volume of one surface multiplied by two provides a relatively fair approximation of the maximum possible natural gap within the evaluated area.

The results of the computation of the void volume and the maximum possible natural gap for each surface quality can be found in Tables 5 and 6 respectively. On the basis of the results, it can be concluded that the gap did not play a major role in the achievement of higher penetration in the samples with surface quality 4. As can be seen in Table 6, the maximum possible natural gap due to the roughness of surface quality 4 is considerably lower than that of surface quality 1 with 0.3 or 0.5 mm pre-set gap. This implies that the natural gap, in the joints with surface quality 4, is not mainly responsible for the increase in travel speed. In fact, a joint prepared with surface quality 1 and 0.15 mm pre-set gap would be equivalent to a joint with a sand-blasted laser cut surface and zero pre-set gap. However, if these two are compared, the latter would provide approximately 80% higher travel speed as well as easier setup because it does not require the preparation of pre-set gap and makes the welding operation more convenient.

Table 5. Computed void volume for each type of surface in a 24 mm x 24 mm area.

	Surface quality 4	Surface quality 3	Surface quality 2	Surface quality 1
Void volume (mm^3)	55	43	26	9

Table 6. Maximum possible (volumetric) natural gap of the joints according to each surface type in a 24 mm x 24 mm area.

	Without pre-set gap				With pre-set gap		
	Surface quality 4	Surface quality 3	Surface quality 2	Surface quality 1	Surface quality 1 with 0.1 mm gap	Surface quality 1 with 0.3 mm gap	Surface quality 1 with 0.5 mm gap
Max. natural gap (mm^3)	110	86	52	18	76	190	306

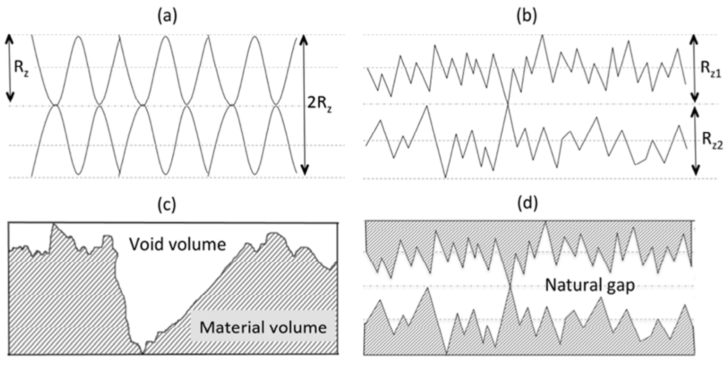


Fig. 8. (a) Schematic 2D roughness profile of milled surfaces. Maximum local gap can be estimated by $2R_z$. (b) Schematic 2D roughness profile of laser cut surface. (c) Definition of void volume for 3D computation of natural gap. (d) schematic of 2D natural gap.

3.2. Sand-blasting effect

The other reason that could explain the increase in travel speed was the effect of sand-blasting on the quality 4 surfaces. For this reason, the welding experiments on surface quality 4 samples were repeated except that this time surfaces were not sand-blasted. Similarly, the other experiments on surface qualities 1, 2, and 3 were also repeated with sand-blasted surfaces. To allow comparison with the data in Figure 6, the same set of welding parameters was used for each corresponding surface type. Figure 9 shows the effect of sand-blasting for each surface type according to the maximum travel speed for full penetration. As can be seen sand-blasting could slightly increase the welding efficiency when samples with surface quality 1, 2, and 3 used for welding. This could be due to the presence of silica on the surfaces or an increase in surface roughness due to the effect of sand-blasting process. However, surprisingly sand-blasting did not have any effect on the maximum travel speed for full penetration when the samples having laser cut surface were used for welding. Therefore, in the case of experiments with surface quality 4, sand-blasting was not responsible for the increase in travel speed compared with the other experiments. It is worth mentioning that sand-blasting had a favorable effect on eliminating pores in the weld. In some cases that samples with surface quality 4 were not sand-blasted, pores appeared in the welds due to the presence of oxide layer.

3.3. Surface pattern effect

Considering the fact that natural gap in the joints could not solely lead to an increased travel speed, and also the fact that sand-blasting on the surfaces had only a minor effect on increasing travel speed, one can argue that the effect of surface pattern could be predominantly the main explanation for this phenomenon. In fact, the chaotic patterns of the vertical striations on the laser cut surfaces could lead to increased laser absorption and at the same time guided the molten filler material flow further inside the joint. This fact together with the presence of the natural gap caused by the laser cut striations in the joint could have increased the welding efficiency or the maximum travel speed for full penetration. A closer look at the surface patterns in Figure 4 (b) shows that within a 1 mm^2 area, e.g. in a groove located between two peaks, the local surface is rather flat compared to a 1 mm^2 area on the laser cut surface in Figure 5 (b) where the variation of surface height is more violent. This could have modulated the incidence of laser beam and material, especially at the deeper parts of the weld where the laser dominated area determines the weld penetration.

4. Conclusion

A number of hybrid laser welding experiments were carried out on 25 mm steel plates according to industrial procedures. The effect of different joint preparation methods was studied, including various edge surface roughness values from 4 μm to 30 μm and different surface roughness patterns. The results were compared with the conventional preparation methods with milling and the use of pre-set gap for increasing penetration. The following conclusions can be drawn:

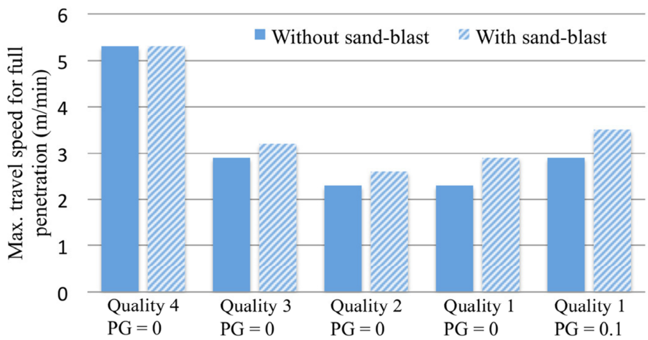


Fig. 9. Comparison of sand-blasting effect for each surface quality based on maximum travel speed for full penetration. PG: pre-set gap.

- Preparation of edge surface quality can be considered as an alternative approach to increase the efficiency of hybrid laser welding. In comparison with commercial preparation methods with milling machines, it is possible to achieve up to 130% increase in welding travel speed by using plates with laser cut-edge surface and no pre-set gap. In addition, using this approach allows welding with zero pre-set gap, which makes it easier to position workpieces. This is because the natural gap caused by the rough striations of the laser cut surface compensates for the lack of pre-set gap.
- An approximation of the natural gap caused by the rough striations of the laser cut surface showed that a joint with laser cut edge surfaces and zero pre-set gap has the same gap volume (at its maximum) as a joint prepared using commercial milling methods and a 0.15 mm pre-set gap.
- Increase in the average surface roughness, within the range of 9 to 30 µm, cannot solely increase the hybrid laser welding efficiency. In fact, at the higher roughness values it seems that the effect of surface roughness patterns on the efficiency of the hybrid laser welding process is more noticeable compared with the effect of average surface roughness value itself. In this experiment, the chaotic vertical striations caused by laser cutting could lead to higher welding travel speed compared with the systematic square shaped pattern caused by milling tools.
- Solidification cracks were found in the welds, regardless of their surface preparation method. The cracks occurred because the welding travel speed range used in this study was too high, leading to high cooling rates and low width-to-depth ratios. In some cases, the cracks appeared as small vertical flaws in the laser-dominated area and they were even too small to be detected by radiographic examination.

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